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BART'S OPERATING ENERGY CONSUMPTION

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The BART Impact Program is a comprehensive, policy-oriented study and evaluation of the impacts of the San Francisco Bay Area's new rapid transit system (BART).

The program is being conducted by the Metropolitan Transportation Commission, a nine-county regional agency established by state law in 1970.

The program is financed by the U. S. Department of Transportation, the U. S. Department of Housing and Urban Development, and the California Department of Transportation. Management of the Federally funded portion of the program is vested in the U. S. Department of Transportation.

The BART Impact Program covers the entire range of potential rapid transit impacts, including impacts on traffic flow, travel behavior, land use and urban development, the environment, the regional economy, social institutions and life styles, and public policy. The incidence of these impacts on population groups, local areas, and economic sectors will be measured and analyzed. Finally, the findings will be interpreted with regard to their implications for the planning of transportation and urban development in the Bay Area and other metropolitan areas.

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BART IMPACT PROGRAM

BART'S OPERATING ENERGY CONSUMPTION

JANUARY 1977
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WORKING PAPER

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U.S. DEPARTMENT OF TRANSPORTATION

AND

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WASHINGTON, D.C.

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BART Impact Program
Transportation System and Travel Behavior Project

BART's Operating Energy Consumption
Prepared by
Peat, Marwick, Mitchell & Co.

January 1977

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The Metropolitan Transportation Commission is the prime contractor for the BART Impact Program. Peat, Marwick, Mitchell & Co. is the subcontractor responsible for the Transportation System and Travel Behavior Project.

16. Abstract BART, the 71-mile Bay Area Rapid Transit System, serving San Francisco, Oakland, and other cities and communities, is the first regional-scale rapid transit system to open in the United States in over 50 years. Service began in 1972. This report is one of a series assessing the impact of BART on transportation and travel in the Bay Area.

The report gives information on BART's operating energy consumption and incorporates an earlier BART Impact Program Report ("Analysis of BART's Energy Consumption for Interim System Operations", June 1975). The updated report was presented as a paper to the January 1977 annual meeting of the Transportation Research Board. It gives a historic analysis of BART's operating energy consumption per passenger-mile and per car-mile. BART's traction energy consumption is compared with that of (1) other rail transit systems, and (2) bus and automobile, in terms of equivalent gallons of petroleum fuel. BART's impacts on total energy consumed by BART, bus and automobile for transbay travel between San Francisco and Oakland is analyzed using data on travel patterns with and without BART.

Although BART carries 20% of all passenger-trips in the transbay corridor, it has reduced overall energy consumption by only 5%. This saving is relatively small because, although BART consumes less energy per passenger-mile than automobile, it consumes more than bus. BART's ridership is drawn about equally from automobile and bus. BART has also had the effect of inducing new trips by automobile.

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BAY AREA RAPID TRANSIT SYSTEM

PEAT, MARWICK, MITCHELL & CO.
SAN FRANCISCO

PREFACE

This report was a product of the Transportation System and Travel Behavior (TSTB) Project of the BART Impact Program. This 1977 revision of the analysis of BART's operating energy consumption updates information contained in the earlier TSTB report, "Analysis of BART's Energy Consumption For Interim System Operations," which is incorporated here as an appendix.

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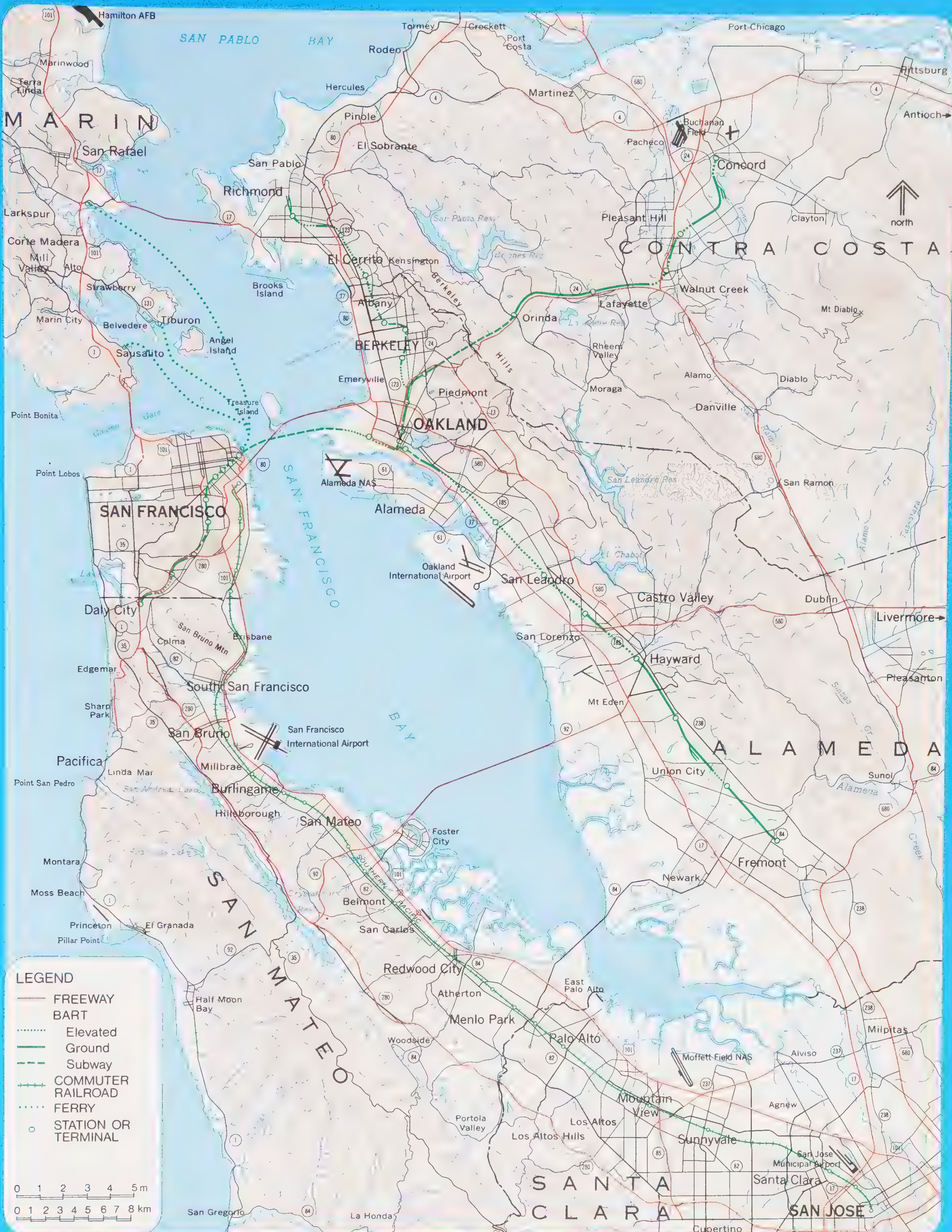

SAN FRANCISCO BAY REGION
CENTRAL AREA

Metropolitan

BART: The Bay Area Rapid Transit System

Length: The 71-mile system includes 20 miles of subway, 24 miles on elevated structures and 27 miles at ground level. The subway sections are in San Francisco, Berkeley, downtown Oakland, the Berkeley Hills Tunnel and the Transbay Tube.

Stations: The 34 stations include 13 elevated, 14 subway and 7 at ground level. They are spaced at an average distance of 2.1 miles: stations in the downtowns are less than one-half mile apart, while those in suburban areas are two to four miles apart. Parking lots at 23 stations have a total of 20,200 spaces. There is a fee (25 cents) at only one of the parking lots. BART and local agencies provide bus service to all stations.

Trains: Trains are from 3 to 10 cars long. Each car is 70 feet long and has 72 seats. Top speed in normal operations is 70 mph with an average speed of 38 mph including station stops. All trains stop at all stations on the route.

Automation: Trains are automatically controlled by the central computer at BART headquarters. A train operator on board each train can override automatic controls in an emergency.

Magnetically encoded tickets with values up to $20 are issued by vending machines. Automated fare gates at each station compute the appropriate fare and deduct it from the ticket value.

Fares: Fares range from 25 cents to $1.45, depending upon trip length. Discount fares are available to the physically handicapped, children 12 and under, and persons 65 and over.

Service: BART serves the counties of Alameda, Contra Costa and San Francisco, which have a combined population of 2.4 million. The system was opened in five stages, from September 1972 to September 1974. The last section to open was the Transbay Tube linking Oakland and the East Bay with San Francisco and the West Bay.

Routes are identified by the terminal stations: Daly City in the West Bay, Richmond, Concord and Fremont in the East Bay. Trains operate from 6:00 a.m. to midnight on weekdays, every 12 minutes during the daytime on three routes: Concord-Daly City, Fremont-Daly City, Richmond-Fremont. This results in 6-minute train frequencies in San Francisco, downtown Oakland and the Fremont line where routes converge. In the evening, trains are dispatched every 20 minutes on only the Richmond-Fremont and Concord-Daly City routes. Service is provided on Saturdays from 9 a.m. to midnight at 15-minute intervals. Future service will include a Richmond-Daly City route and Sunday service.* Trains will operate every six minutes on all routes during the peak periods of travel.

Patronage: Approximately 146,000 one-way trips are made each day. Approximately 200,000 daily one-way trips are anticipated under full service conditions.

Cost: BART construction and equipment cost $1.6 billion, financed primarily from local funds: $942 million from bonds being repaid by the property and sales taxes in three counties, $176 million from toll revenues of transbay bridges, $315 million from federal grants and $186 million from interest earnings and other sources.

March 1978

*Sunday service began in July, 1978

BART'S OPERATING ENERGY CONSUMPTION

Introduction

Much discussion has focused recently on the relative fuel efficiency of various urban passenger transport modes.* The primary purpose of this paper is to contribute to this discussion by documenting and analyzing the operating energy consumption of the San Francisco Bay Area's new rapid transit system (BART). The paper briefly compares BART's energy consumption to that of other rail rapid transit systems and includes a partial analysis of energy consumption of BART, bus, and automobile in one travel corridor of the Bay Area using recent data on actual passenger bolumes.**

Data presented in this paper were assembled as part of the BART Impact Program, a comprehensive study and evaluation being conducted by the Metropolitan Transportation Commission, Berkeley, under the sponsorship of the U.S. Department of Transportation and the U.S. Department of Housing and Urban Development. Peat, Marwick, Mitchell & Co. are prime contractors to the Metropolitan Transportation Commission with responsibility for analysis of BART's impacts on the transportation system and on travel behavior.***

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*See References: Stuntz and Hirst (1976), Hirst (1976), DeLeuw Cather & Company (1976(.

**Results and conclusions given here update those contained in earlier reports of the BART Impact Program. See: Peat, Marwick, Mitchell & Co. (1976).

***The author gratefully acknowledges the assistance of Bay Area Rapid Transit District staff in providing data and for helpful review comments on an early draft of the paper. However, errors and all conclusions are the responsibility of the author. The views expressed do not necessarily represent those of Peat, Marwick, Mitchell & Co., the Metropolitan Transportation Commission, or the BART Impact Program's sponsors.

BART'S OPERATING ENERGY CONSUMPTION

This section is concerned only with the energy consumed in operating BART. While it is unquestionably important in an overall assessment, the energy consumed in constructing the System is not considered.*

Components of Operating Energy

As discussed in this paper, the total energy consumed in operating BART comprises:

- Station Energy. This is the energy consumed in operating and lighting the BART stations, parking lots, and administration building and ventilating the Transbay Tube and Berkeley Hills Tunnel.

- Maintenance Energy. This is the energy required to repair and maintain the transit vehicles and other equipment and provide heat and light for the four maintenance shops. Energy drawn from the third rail in the maintenance yards is excluded.

- Traction Energy. This is all energy drawn from the third rail (1,000 volts d.c.) to propel the BART cars and to power the cars' auxiliary functions such as air conditioners, heaters, and lights. Propulsion energy is consumed during revenue service hours and during nonrevenue service hours for testing. Auxiliary energy is consumed at all times by the cars (except those in the shop for major repairs) since air conditioning, heating, and lighting equipment is always left on.

Historical Trends

Total Operating Energy. Figure 1 shows the three components of BART's monthly operating energy consumption from the start of service in 1972 to early in 1976. Maintenance energy makes up a small part of

*For discussions of total energy consumed in construction and operation see references: Fels (1974), Healy (1974), Healy and Dick (1974), Lave (1977).

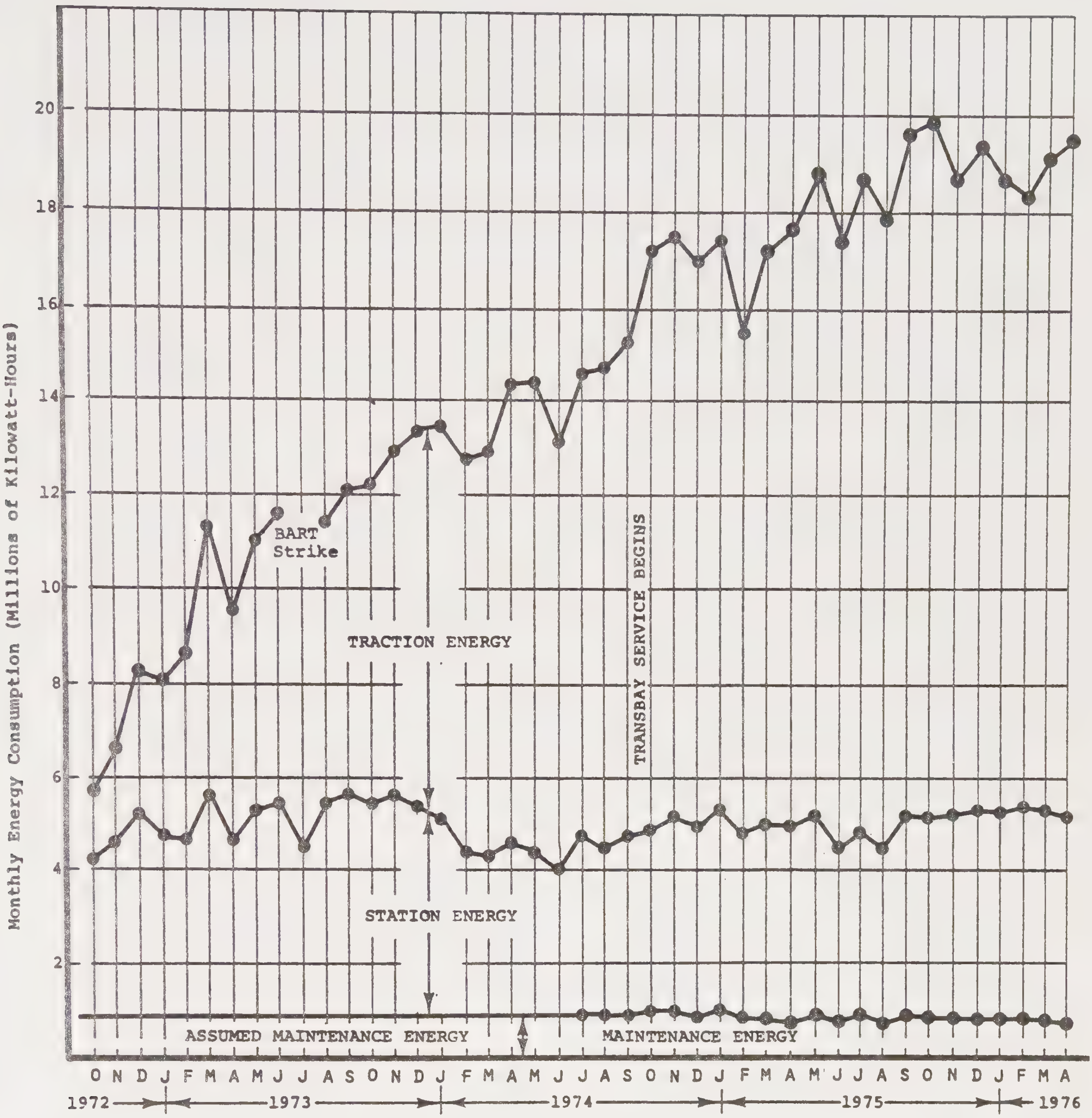

FIGURE 1

HISTORICAL BART MONTHLY ENERGY CONSUMPTION

Source: ● Peat, Marwick, Mitchell & Co. Analysis of data provided by BARTD Engineering Department.

the total and has been fairly constant over the period, averaging 0.9×10^6 kwh monthly. Station energy consumption has fluctuated as a result of varying degrees of construction activity at unopened stations, as stations have opened for service, and as a result of energy conservation measures adopted at the time of the "energy crisis" in the winter of 1973-1974. With all stations except Embarcadero open for service, monthly station energy consumption is now steady, averaging 4.3×10^6 kwh over the year May 1975 to April 1976. Corresponding to a rise in the number of cars in service and car-miles operated, traction energy has increased to a monthly level of 14.1×10^6 kwh in April 1976.

Over the year May 1975 through April 1976, monthly traction energy consumption averaged 13.6×10^6 kwh, 72% of the total monthly operating consumption of 18.8×10^6 kwh; station energy averaged 4.3×10^6, 23% of the total; and maintenance energy averaged 0.9×10^6 kwh, 5% of the total.

Operating Energy per Car-Mile. Figure 2 graphs BART's total monthly operating energy consumption and the traction energy component per car-mile from October 1972 through April 1976. As might be expected, traction energy per car-mile has remained fairly steady over the period, with fluctuations caused by changes in train sizes, operating conditions, and the number of cars in operation. As the relatively constant station and maintenance energy have been distributed over an increasing number of car-miles, total energy per car-mile has decreased, but has been fairly steady since transbay BART began. Over the year from May 1975 to April 1976, car-miles per month averaged 1,908,000. Correspondingly, total operating energy averaged 9.9 kwh per car-mile, and traction energy 7.1 kwh per car-mile.

Operating Energy per Passenger-Mile. As shown in Figure 3, the trends in BART's total operating and traction energy consumption per passenger-mile are similar to the per car-mile figures in Figure 2. The large drop when transbay BART service started reflects the addition of longer-distance transbay trips. Figure 3 shows energy consumption as fairly constant (possibly displaying a slight upward trend) from May 1975 to April 1976.

As graphed on Figure 4, BART's monthly ridership between May 1975 and April 1976 was fairly constant except during April 1976 when normal ridership patterns were distorted by a strike involving the MUNI transit system in San Francisco.* Average ridership over the

*Ridership lost as a result of the 16% fare increase (effective November 3, 1975) appears to have been offset by evening ridership (8:00 p.m. to 12:00 midnight service began effective November 28, 1975).

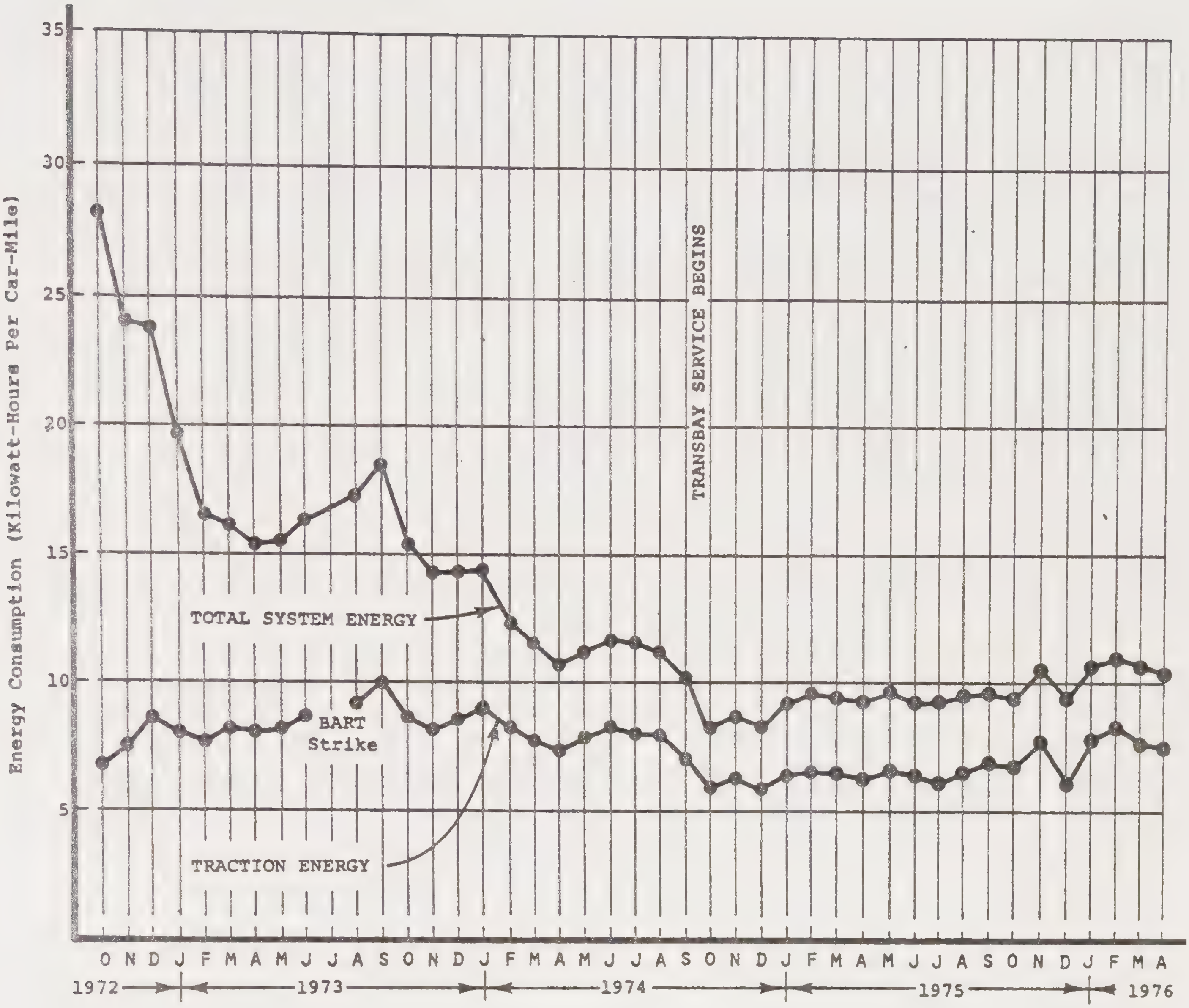

FIGURE 2

BART ENERGY CONSUMPTION PER CAR-MILE

Source: • Peat, Marwick, Mitchell & Co. Analysis of data provided by BARTD Engineering Department.

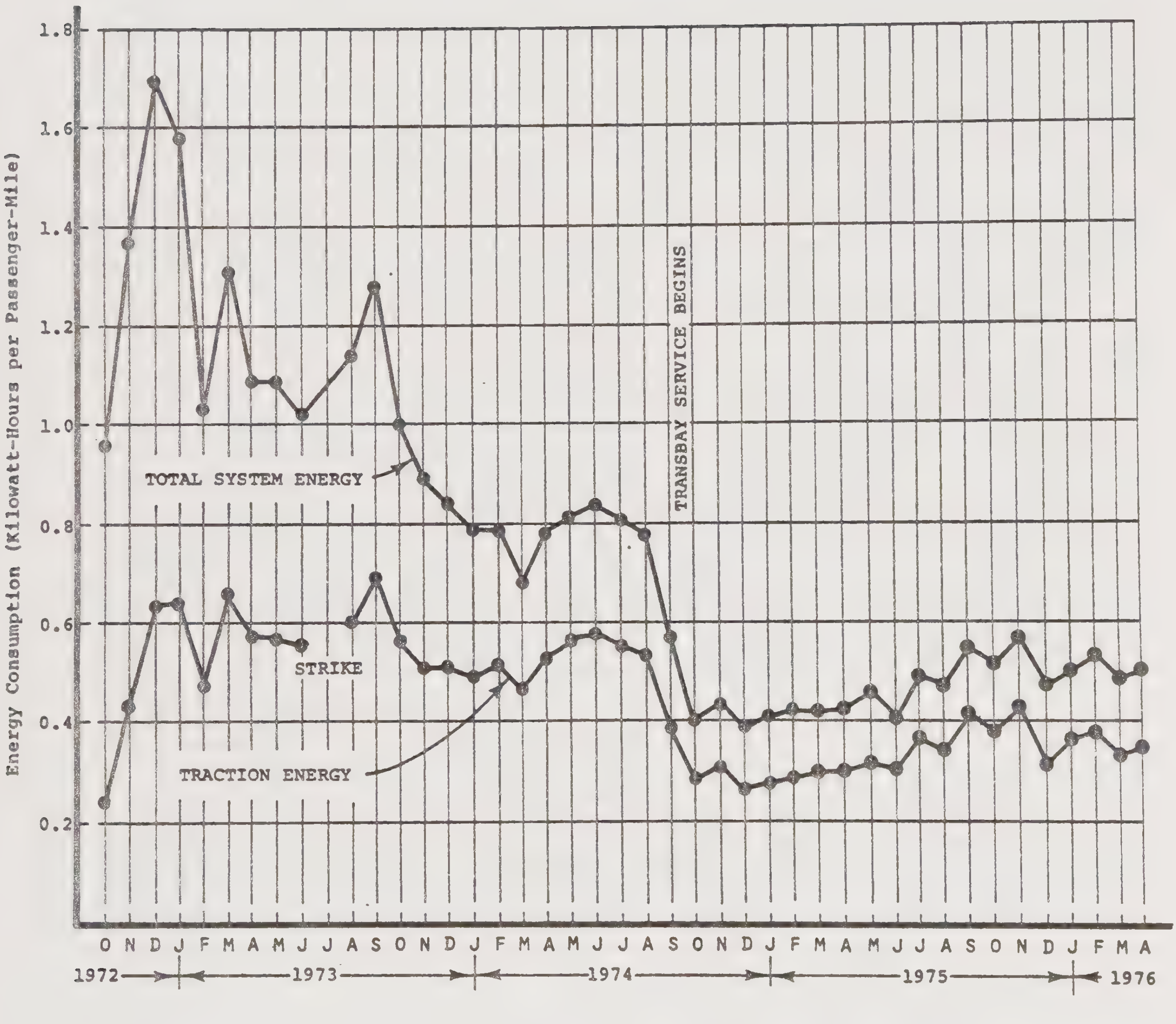

FIGURE 3

BART ENERGY CONSUMPTION PER PASSENGER-MILE

Source: • Peat, Marwick, Mitchell & Co. Analysis of data provided by BARTD Engineering Department.

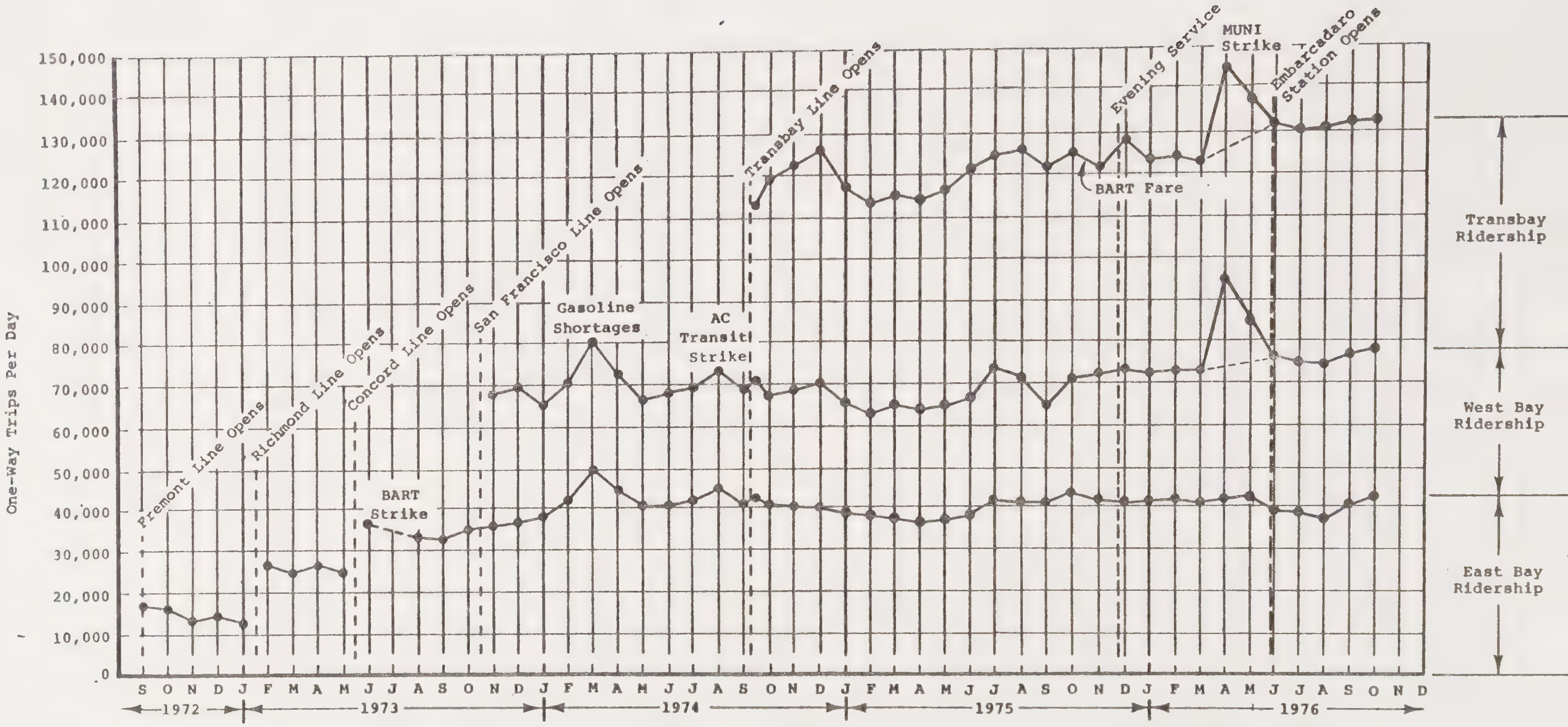

FIGURE 4

AVERAGE DAILY BART RIDERSHIP, SEPTEMBER 1972 - OCTOBER 1976

Source: ● BARTD Office of Research, Monthly BART Patronage Reports.

11-month period May 1975 through March 1976 was 2.65 million trips per month (123,000 trips per day), and average trip length was 13.7 miles, giving an average passenger-mile-per-month estimate of 36.20 million. Dividing total operating energy consumption traction energy consumption estimates shown in Figure 1 by this passenger-mile estimate gives averages of 0.52 kwh per passenger-mile total operating energy and 0.38 kwh per passenger-mile traction energy consumption for the year ending April 1976.

Estimates of BART's Future Operating Energy Consumption

The analyses of the previous section suggest that at current service levels, BART's operating energy consumption is fairly stable from month to month, especially when expressed per car-mile. "Current service levels" means an average of 1.91 million car-miles per month provided by a total fleet of 450 cars over 90 hours of revenue service per week (i.e.,6:00 a.m. to 12:00 midnight five days a week). BART's target for ultimate operations with the existing 450-car fleet is a level of 3.24 million car-miles per month (an increase of 70% over current levels) operated over 140 hours per week (5:00 a.m. to 1:00 a.m., seven days a week).* If this service level were reached, BART's total operating energy consumption would be about 24.0×10^6 kwh per month, as summarized in Table 1. Table 1 also gives projected energy consumptions per car-mile and per passenger-mile (assuming passenger-miles increase in proportion to car-miles).

The calculations underlying the projections in Table 1 assume that station and maintenance energy consumption are essentially fixed and will increase only slightly as service is increased and hours of service extended. As shown previously, traction energy per car-mile has been fairly constant over all phases of BART's operations to date, and, assuming operating procedures remain about the same in the future, traction energy per car-mile should also remain similar.

The one major change in operations which might have an appreciable effect would be effective use of regenerative braking. All BART vehicles are equipped with regenerative braking equipment designed to return power to the System during braking. To date, the regenerative braking system has been largely ineffectual in reducing BART's energy consumption because of the relatively large spacing between trains and because the power supply system has been separated into distinct "blocks," thereby

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*This is the "Phase IV" service level described in BARTD "Draft Five-Year Plan Overview" of April 1976. However, more recent BARTD projections do not now envisage this level being reached until well beyond the five-year planning horizon.

Table 1

BART ENERGY CONSUMPTION AT CURRENT AND PROJECTED SERVICE LEVELS

	Energy Consumption		
	Total per Month (kwh x 10^6)	Per Car-Mile (kwh)	Per Passenger-Mile (kwh)
Current BART[a]			
Traction Energy	13.6	7.1	0.38
Station Energy	4.3	2.3	0.12
Maintenance Energy	0.9	0.5	0.02
Total	18.8	9.9	0.52
Projected BART[b]			
Traction Energy	18.5	5.7	0.30
Station Energy	4.5	1.4	0.07
Maintenance Energy	1.0	0.3	0.02
Total	24.0	7.4	0.39

a. Average for May 1975 to April 1976: 1.91 million car-miles per month, 36.2 million passenger-miles per month.

b. Ultimate service with existing 450-car fleet: 3.24 million car-miles per month, 61.4 passenger-miles per month, 20% average reduction in traction energy consumption per car-mile due to regenerative bracking.

prohibiting the flow of power from a decelerating train to an accelerating train if the trains are in different blocks. As train spacings are reduced and the blocking of the power system is eliminated, the regenerative braking system will act as a power source and reduce net external power requirements. Full information on the potential energy savings from regenerative braking is not yet available, but recent evidence suggests that it could reduce traction energy per car-mile by as much as 40% during peak operating periods (i.e., at minimum headways), and by an average of 20% for all operating periods (peak and off-peak).* Consequently, the calculations underlying Table 1 assume traction energy per car-mile will be reduced to 80% of its current level for projected full-service operations.

Table 1 suggests that at projected full-service levels, BART's monthly traction energy consumption will be 18.5 kwh x 10^6 and total monthly operating energy consumption will be 24.0 kwh x 10^6. Per car-mile, traction energy consumption will be 5.7 kwh (a 20% reduction from current levels) and total operating energy consumption will be 7.4 kwh (a 25% reduction from current levels). These energy consumption estimates are somewhat higher than previous estimates based on data for BART's early operations,** even though the future savings from regenerative braking are assumed to be greater than previously supposed.

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*A recent BARTD memorandum reports that "In July, 1976 a test car equipped with monitoring instruments was run, spaced three minutes behind another BART car to test the efficiency of regenerative braking at 3-minute headways. This was a partial test, since there was no car behind the test car to pick up additional energy, and few trains operating in the opposite direction to make use of the braking energy. The results of the test indicated that a significant reduction in energy use had been achieved by regenerative braking, despite these limitations, and despite the blocking of the power supply which will be eliminated in the future. A reduction of between 30-40% of the energy into the test car was achieved. This is equivalent to roughly an 18% reduction of total traction energy usage."

**See Healy (1973), p. 7 where an "upper bound" estimate of 5.5 kwh per car-mile is given for traction energy, and Peat, Marwick, Mitchell & Co. (1976), p. 49, where an estimate of 5.1 kwh per car-mile is given.

Comparison of Traction Energy Consumed by BART and Other Rail Transit Systems

Comparing BART's energy consumption with that of other rail rapid transit systems is difficult given (1) differences in methods used by different systems to account for their consumption, and (2) differences in the operating conditions involved. However, Table 2 attempts such a comparison of aggregate energy consumption. The data for BART are as given earlier in this paper, and the data for the other systems are as provided by the respective operators or are taken from published reports. Since data on station and maintenance energy consumptions are not readily available for the other systems, only traction energy consumption is shown in the table. In BART's case, traction energy currently makes up 72% of total operating energy, and at projected full-service levels will be about 80%.

Given differences in car sizes, seating capacities, and passenger load factors of the various systems, choice of an appropriate unit for comparing traction energy consumption is also problematic, since any production unit tends to be biased for or against any given system. In an attempt to provide the basis for a fair comparison, Table 2 shows energy consumption for three production units: car-miles, seat-miles, and passenger-miles.

A complex of factors accounts for the differences in energy consumption per car-mile among the systems, some of the most important being vehicle weight, frequency of stops (station spacing), acceleration rate, and top speed. Thus, the Lindenwold Line, with its high average speed and heavy cars has a fairly high traction energy consumption per car-mile (although still slightly less than BART's current consumption). On the other hand, the Chicago system, with its frequent stops and high acceleration rates, has lower traction energy per car-mile than BART, reflecting Chicago's lighter vehicles.

BART's current traction energy consumption per car-mile of 7.1 kwh is slightly higher than the average for the other systems, but reflecting its much higher seating capacity, BART's traction energy consumption of 1.0 kwh per seat-mile is much lower than the average for the other systems. When differences in passenger load factors (i.e., passengers per seat) are taken into account, BART's energy consumption of 0.4 kwh per passenger-mile becomes higher than for the other systems shown. In short, bearing in mind the large number of factors that affect the comparison, BART's current traction energy consumption is consistent with that of other U.S. rapid rail transit systems, and, if the potential savings from regenerative braking can be realized, will probably be rather lower than the average.

Table 2

TRACTION ENERGY CONSUMPTION: COMPARISON OF BART AND OTHER RAIL TRANSIT SYSTEMS

System	Typical Vehicle Weight (lbs)	Seats per Car	Average Station Spacing (miles)	Average Speed (mph)	Yearly Car-Miles (millions)	Yearly Passengers (millions)	Average Trip Length (miles)	Yearly Passenger-Miles (millions)	Total Electricity Consumed (millions kwh)	Energy Consumed per Production Unit: Kwh per Car-Mile	Kwh per Seat-Mile	Kwh per Passenger-Mile
Chicago (CTA)	42,000	49	0.7	23	48.78	128.24	7.2	923.3	225.4	4.62	0.094	0.24
New York City (MTA)	79,000	44	0.5	19	320.54	1,096.00	5.7	6,204.4	1,681.0	5.24	0.119	0.27
Cleveland (CTS)	55,000	54	1.1	24	3.68	10.88	n.a.	n.a.	31.1	8.45	0.157	n.a.
New York-New Jersey (PATH)	50,000	35	1.2	19	10.51	37.77	6.7	253.6	66.6	6.37	0.182	0.26
PATCO (Lindenwold Line)	78,000	78	1.2	39	4.31	11.11	8.5	94.4	29.7	6.90	0.088	0.31
BART	57,000	72	2.1	38	22.90	31.75	13.7	434.4	163.4	7.14	0.099	0.38

Sources: BART: Peat, Marwick, Mitchell & Co. analysis of data provided by BART District for May 1975-April 1976, with adjustments made to account for distorting effects of MUNI strike, April 1976.

Other Systems: American Public Transit Association, 1974 Transit Operating Report.
N. D. Lea Transportation Research Corporation, Lea Transit Compendium: Heavy Rail Transit, 1974.
U.S. Department of Transportation, 1972 National Transportation Report.
Information obtained from respective transportation organizations, June 1976.

Comparison of Traction Energy Consumed by BART, Bus, and Automobile

Assumptions of Comparisons. Finding an appropriate basis for comparing BART's energy consumption with that of other urban transportation modes is even more difficult. Because of the different fuel sources involved, different fuel efficiency of vehicles, differences in the characteristics of transportation service provided, and variations in passenger loadings, a large number of assumptions, are necessary, any one of which represents only one point in a range of possibilities. Clearly, conclusions must be drawn extremely cautiously in view of the uncertainties and limitations of the assumptions. The brief analysis given in this section is based on the following assumptions.

Table 3 compares BART with automobile and bus on the basis of (1) fuel input to generating plants producing electricity for use by BART, and (2) fuel input directly to automobiles and buses. Thus, the comparison does not take into account the energy required to refine, process, and transport fuels for use in power plants or vehicles. This energy is difficult to estimate, but refining losses may amount to 15% of the fuel's original heating content.

The following assumptions are made about the energy content of the various source fuels and the efficiencies with which they are converted to usable energy:

1. One gallon of fuel (whether fuel oil used as input to an electricity-generating plant, in a gasoline-powered automobile or in a diesel bus) is assumed to have an energy content or heating value of 136,000 British thermal units (Btu). This is an average figure; different petroleum products typically have heating values varying between 125,000 Btu per gallon and 150,000 Btu per gallon depending on the processing form and quality of unrefined fuel.

2. Fuel is assumed to be converted to usable electrical energy for use by BART with an efficiency of 34% (i.e., losses in generation and transmission amount to 66% of the input energy). (Again, this is not a precise value; efficiencies of between 25% and 35% are commonly quoted.) In other words, fuel with a heating value of 10,000 Btu is required as input to a power plant to produce 1 kwh (3,415 Btu) of electrical energy at the point of use.

Combining assumptions 1 and 2 gives the result that 1 kwh of electrical energy, at the point when BART uses it, requires 0.074 gallons of fuel to be input to an (oil-fired) power plant. In the following discussion, the energy consumed by BART and other transport modes is compared in terms of "equivalent gallons of fuel" using the above assumptions.

Table 3

TRACTION ENERGY CONSUMPTION IN EQUIVALENT GALLONS OF FUEL: COMPARISON OF BART, BUS, AND AUTOMOBILE

	Seats per Vehicle	Gallons per Car-Mile	Gallons per Seat-Mile
BART	72	0.528	0.0073
AC Transit (Oakland)	48	0.206	0.0043
Automobile			
Luxury (9.8 mpg)	6	0.102	0.0170
Standard (15.7 mpg)	5	0.064	0.0128
Compact (19.6 mpg)	4	0.051	0.0128

Sources:

BART: Peat, Marwick, Mitchell & Co. analysis of data provided by BART District for May 1975-April 1976; 1 kwh assumed equivalent to 0.074 gallons.

Bus: American Public Transit Association, 1974 Transit Operating Report.

Automobile: U.S. Department of Transportation, Energy Statistics, August 1974.

A number of commentators have pointed out that this is not an altogether fair basis for comparison since electrically-powered rail transit systems do not necessarily use oil as their fuel source, while automobiles and buses do. (Indeed, perhaps 50% of BART's energy is from hydroelectric sources.) If the point of the analysis is strictly to compare the relative efficiency of different modes' oil consumption, the objection is valid. However, in this discussion, we take a broader view and assume that energy used by different transport modes can and should be compared directly, irrespective of the fuel used as its source. This being the case, equivalent gallons of fuel oil are as convenient units for comparison as any.

Comparisons are made only for propulsion (traction) energy consumed by BART, bus, and automobile--energy required in the construction and maintenance of facilities and vehicles is excluded.

Energy Consumption per Vehicle-Mile and per Seat-Mile. Table 3 compares the current BART system with the Oakland bus system (AC Transit)* and three representative automobiles, "luxury" (9.8 miles per gallon), "standard" (15.7 miles per gallon), and "compact" (19.6 miles per gallon), on the basis of their traction energy per vehicle-mile and per seat-mile.

In terms of fuel consumed per seat-mile of service provided, BART's performance (0.007 gallons per seat-mile) is shown to be considerably poorer than AC Transit's systemwide average (0.004 gallons per seat-mile), but a great deal better than automobile (between 0.013 and 0.017 gallons per seat-mile). However, these figures tell us only about potential fuel efficiencies. They tell us very little about relative fuel efficiencies actually achieved since they do not incorporate the all-important variable, load factor, i.e., the proportion of the seats being used to carry passengers. A fully loaded BART train is many times more fuel-efficient per passenger-mile than a luxury automobile with only one person in it, but a half-empty BART train is less fuel-efficient per passenger-mile than an economy car with four people in it. (That is, just about any desired conclusion can be reached if appropriate load-factor assumptions are made.)

Energy Consumptions per Passenger-Mile. As a means of comparing the relative fuel efficiencies of BART, bus, and automobile per passenger-mile under realistic assumptions of load factors, this section analyzes

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*AC Transit provides service between San Francisco and Oakland across the Bay Bridge as well as within Oakland, Berkeley, and their suburbs. Largely because its average speed, systemwide, is higher than many other systems, AC Transit bus fuel consumption is slightly better but not atypical of other bus systems.

travel in one of the major commuter corridors in the Bay Area--between San Francisco and Oakland. Passenger travel by BART (through the Transbay Tube), and by bus and automobile (across the Bay Bridge) is included, but not passenger travel in trucks. Total travel in both directions between 6:30 a.m. and 6:30 p.m. is analyzed in three categories:

- Peak Period/Peak Direction. Travel to San Francisco (westbound) between 6:30 a.m. and 9:00 a.m. and from San Francisco (eastbound) between 4:00 p.m. and 6:30 p.m.

- Peak Period/Reverse Direction. Travel eastbound between 6:30 a.m. and 9:00 a.m. and westbound between 4:00 p.m. and 6:30 p.m.

- Off-Peak. Travel in both directions between 9:00 a.m. and 4:00 p.m.

Table 4 summarizes transbay travel in each of these categories.

During the peak periods, in the peak direction of travel, transbay person-trips are split almost evenly between automobile and transit, with automobile carrying 49% of the total, bus 25%, and BART 26%. However, in the reverse direction, the peak-period distribution is very different, with automobile carrying 82% of trips, bus 6%, and BART 12%. During the off-peak, the split is automobile 77%, bus 6%, and BART 17%.

In the peak period/peak direction, BART achieves an average occupancy of 68 passengers per car (94% of available seats); buses carry an average of 36 passengers each (74% of seats); and automobiles have an average occupancy of 1.47 (29% of an assumed five seats per car). Thus transit, and especially BART, carries passengers in the peak period/peak direction a great deal more efficiently in terms of passengers per available seat.

However, this efficiency is offset by the extremely low load factors in the peak period/reverse direction. On average, there are 11 passengers per BART car (15% seat occupancy), 9 passengers per bus (20% occupancy), and 1.30 persons per automobile (26% occupancy of 5 seats). In other words, the automobile is nearly twice as efficient in terms of passengers carried per available seat.

In the off-peak period, BART's average seat occupancy is 41%, bus' 35%, and automobile's 27%.

Table 5 translates these occupancies into fuel consumptions expressed in gallons per passenger-mile for each of the three categories of travel.

Table 4

PASSENGER TRAVEL BY AUTOMOBILE, BUS, AND BART
BETWEEN SAN FRANCISCO AND OAKLAND

		Passenger Travel by			
		Automobile	Bus	BART	Total
	Seats per Vehicle	5	48	72	
Peak Period/Peak Direction					
Westbound 6:30-9:00 a.m.	Persons	53,060	26,975	27,525	107,560
Eastbound 4:00-6:30 p.m.	Vehicles	36,040	757	406	
	Persons per Vehicle	1.47	35.7	67.9	
	Percent Seat Occupancy	29%	74%	94%	
Peak Period/Reverse Direction					
Eastbound 6:30-9:00 a.m.	Persons	28,940	2,125	4,055	35,120
Westbound 4:00-6:30 p.m.	Vehicles	22,221	225	377	
	Persons per Vehicle	1.30	9.4	10.8	
	Percent Seat Occupancy	26%	20%	15%	
Off-Peak (Both Directions)					
9:00 a.m.-4:00 p.m.	Persons	77,420	5,410	17,290	100,120
	Vehicles	57,640	319	583	
	Persons per Vehicle	1.34	17.0	29.7	
	Percent Seat Occupancy	27%	35%	41%	
Total (Both Directions)					
6:30 a.m.-6:30 p.m.	Persons	159,420	34,510	48,870	242,800
	Vehicles	115,901	1,301	1,366	
	Persons per Vehicle	1.38	26.5	35.8	
	Percent Seat Occupancy	28%	55%	50%	

Source: University of California, Institute of Transportation Studies, Bay Bridge Traffic Survey Series A-46, April 1976.

Table 5

ENERGY CONSUMPTION PER PASSENGER-MILE BY MODE:
SAN FRANCISCO-OAKLAND TRAVEL

	Passenger Travel by		
	Automobile	Bus	BART
(Equivalent) Gallons/Vehicle-Mile	0.064	0.206	0.528
Peak Period/Peak Direction			
Average Vehicle Occupancy	1.47	35.7	67.8
Gallons per Passenger-Mile	0.043	0.006	0.008
Peak Period/Reverse Direction			
Average Vehicle Occupancy	1.30	9.4	10.8
Gallons per Passenger-Mile	0.049	0.022	0.049
Off-Peak (Both Directions)			
Average Vehicle Occupancy	1.34	17.0	29.7
Gallons per Passenger-Mile	0.047	0.012	0.018
Total (Both Directions)			
6:30 a.m.-6:30 p.m.			
Average Vehicle Occupancy	1.38	26.5	35.8
Gallons per Passenger-Mile	0.046	0.008	0.015

Sources: See Tables 3 and 4.

For the peak period/peak direction of travel, BART (0.008 gallons per passenger-mile) is less fuel efficient than bus (0.006 gallons per passenger-mile), but considerably more so than a "standard" (16 mpg) automobile (0.043 gallons per passenger-mile). However, in the peak period/reverse direction, BART's energy consumption per passenger-mile is over twice that of bus and the same as automobile. In the off-peak, BART consumes about 50% more energy than bus per passenger-mile, and only about 40% less than automobile.

Overall, BART's energy consumption of 0.015 gallons per passenger-mile is about one-third of automobile's (0.046 gallons per passenger-mile) but nearly twice that of bus' (0.008 gallons per passenger-mile). BART thus shows a clear advantage in actual energy efficiency over the private automobile (albeit smaller than many have claimed) but compares poorly with the actual per passenger-mile performance of buses over the San Francisco-Oakland Bay Bridge. Translated into total traction energy consumption (assuming an equal trip length for all travelers), automobile consumes 88% of the energy in transporting 66% of the trips, BART consumes 9% in carrying 20% of the trips, and bus consumes 3% in carrying 14% of the trips.

One reason for BART's relatively poor overall energy performance is the very low load factors achieved in the peak period/reverse direction of travel. As shown in Table 4, BART runs trains of approximately the same size (8 cars, 580 seats) and the same headways (6 minutes) in both directions at the peak period, but in the reverse-commute direction each train is carrying an average of only 90 people. The unnecessarily high level of service in the reverse direction is provided because storage capacity for BART trains or cars in San Francisco is very small; essentially all cars run through the Transbay Tube into San Francisco during the morning peak period also have to be run back again "empty." In the evening, the reverse takes place.

In contrast, AC Transit runs only 30% as many buses in the peak period/reverse direction as they do in the peak period/peak direction. The remaining buses are "stored" in San Francisco during the off-peak period. BART provides a much higher level of transit service than bus in the peak period/reverse direction, but at a substantial energy price. Clearly, a large number of automobiles are also stored in San Francisco during the day; about 14,000 more automobiles travel in the peak period/peak direction as do in the peak period/reverse direction.

BART's Impact on Transbay Operating Energy Consumption

Table 6 approximates current traction energy consumed daily in daytime passenger travel between San Francisco and Oakland by automobile, bus, and BART. A nominal average trip length of ten miles is assumed for all trips in the table. A total of 83,800 gallons of fuel (equivalent) is shown as the daily total for all three modes.

Table 6

TOTAL TRANSBAY ENERGY CONSUMPTION WITH BART
April 1976

	Passenger Travel by			
	Automobile	Bus	BART	Total
Peak Period/Peak Direction				
Passengers	53,060	26,975	27,525	107,560
Vehicles	36,040	757	406	
Equivalent Gallons Consumed	22,990	1,560	2,140	26,690
Peak Period/Reverse Direction				
Passengers	28,940	2,125	4,055	35,120
Vehicles	22,221	225	477	
Equivalent Gallons Consumed	14,180	460	1,990	16,630
Off-Peak (Both Directions)				
Passengers	77,420	34,510	17,290	100,120
Vehicles	57,640	1,301	583	
Equivalent Gallons Consumed	36,770	660	3,080	40,510
Total				
Passengers	159,420	34,510	48,870	242,800
Vehicles	115,901	1,301	1,366	
Equivalent Gallons Consumed	73,940	2,680	7,210	83,830

Sources: See Tables 3 and 4; 10-mile average trip length assumed for all trips.

Table 7 approximates total energy consumption, assuming that BART is not available. Trips currently made by BART are assumed to be made by bus and automobile in the following proportions:

	Assumed Distribution of BART Trips Among	
	Bus	Automobile
Peak Period/Peak Direction	75.1%	24.9%
Peak Period/Reverse Direction	40.1	59.9
Off-Peak	41.5	58.5
Total	60.6%	39.4%

These percentages are derived from analyzing the previous mode of travel given by respondents to a survey of transbay travel conducted by the BART Impact Program in October 1974, about six weeks after the start of transbay BART. (Respondents who said they did not make the trip before BART are excluded from the computation.) Note that in the peak period/peak direction, 75% of BART riders are shown as being people who would otherwise ride the bus. In both the peak period/reverse direction and off-peak, about 40% of BART riders would ride the bus, and 60% automobile.* As in Table 6, Table 7 assumes an average trip length of ten miles throughout, and the same total number of trips by all modes. BART travelers who divert to automobile and bus in the "without BART" case are assumed to travel at the same occupancies (persons per vehicle) as for current automobile and bus travel (see Table 4).

Comparing Tables 6 and 7 shows that in the peak period/peak direction travel "with BART" saves about 2,000 gallons per day relative to travel "without BART"—a savings of 7%. However, in the peak period/reverse direction, travel "with BART" uses slightly more energy than "without BART"—because of transit's low load factors. Throughout the day the "with BART" system saves about 4,200 equivalent gallons of fuel for transbay travel—a savings of 5%.

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*More recent survey data suggest that as time goes by, BART draws new transbay riders more from automobiles than from buses—implying that the figures above understate the percentage of BART riders who would use automobile and correspondingly overstate the percentage who would use bus. We have elected to use data on the previous mode of travel from the earlier survey because we feel they more closely represent the distribution of the mode that would be used if BART were not available. This is primarily because an increased proportion of BART travelers in the more recent surveys are people who did not make the trip at all before BART. Thus, no information exists on their likely alternative mode.

Table 7

TOTAL HYPOTHETICAL TRANSBAY ENERGY CONSUMPTION
WITHOUT BART
April 1976

	Passenger Travel by		
	Automobile	Bus	Total
Peak Period/Peak Direction			
Passengers	59,914	47,646	107,560
Vehicles	40,695	1,337	
Equivalent Gallons Consumed	25,960	2,750	28,710
Peak Period/Reverse Direction			
Passengers	31,369	3,751	35,120
Vehicles	24,086	397	
Equivalent Gallons Consumed	15,370	810	16,180
Off-Peak (Both Directions)			
Passengers	87,535	41,685	100,120
Vehicles	65,171	1,724	
Equivalent Gallons Consumed	41,570	1,530	43,100
Total			
Passengers	178,818	63,982	242,800
Vehicles	129,952	3,458	
Equivalent Gallons Consumed	82,900	5,090	87,990

Source: See Tables 3 and 4 and text; 10-mile average trip length assumed for all trips.

Effects of New Trips. The energy savings of 4,200 gallons of fuel daily suggested by Table 7 assumes that the same number of trips (of the same length) are made between San Francisco and Oakland with BART as would be without. In fact, some trips currently being made on BART would not be made if BART were not available. These trips amount to perhaps 5% of total ridership. However, the extra fuel used for these trips is small, especially since many of these new trips are made in the off-peak or peak period/reverse direction and so increase load factors without increasing energy consumption. In total, the extra fuel probably amounts to less than 500 gallons daily.

A more important energy consideration is the fuel associated with additional automobile trips that BART may have induced. BART reduced Bay Bridge traffic volumes, reduced congestion, and improved driving conditions, and this apparently attracted a significant number of "new" automobile trips to the Bridge. Many uncertainties underlie our estimates of the number of these "induced" automobile trips, but they probably represent at least a 5% increase over the automobile vehicle volume without BART (i.e., a daily increase of about 3,000 vehicles in each direction). The extra fuel consumed by these automobiles (again taking a nominal ten-mile average trip length and assuming vehicle fuel consumption characteristics as in Table 5) amounts to an additional 3,700 gallons daily. Thus, when changes in travel patterns associated with BART are taken into account, a negligible change in net operating energy consumption is suggested--the energy savings resulting from diversion of previous travel to BART being offset by increased energy consumption for new trips.

Conclusions. The conclusion that BART gives rise to no significant saving in operating energy consumption is clearly a surprise--or at least contrary to what most proponents of rapid rail transit have argued, and before too much is made of it, it is worth restating the limitations of the analysis presented here.

First, the above discussion concerns traction (propulsion) energy only. The energy consumed in constructing of the BART system is not taken into account (nor are the possible energy savings associated with not constructing buses and automobiles and their associated facilities). Energy consumed in maintenance and other aspects of operation is also excluded.

The analysis concerns traction energy consumption for passenger travel in only one of the corridors served by the BART System. Although the Transbay Tube is the most heavily-traveled link of the BART System (carrying about 40% of all BART ridership), conclusions for this one corridor do not necessarily apply to the System as a whole.

The analysis assumes that the average length of trips made by BART, bus, and automobile is the same and considers only the energy consumed by the "line-haul" mode--energy consumed by automobiles and buses in providing access to BART stations is not included.

In comparing BART, bus, and automobile, a number of assumptions have been made about the energy content of fuels and the efficiency with which they are used by the three modes. This analysis uses an average rate for current BART energy consumption per car-mile (not taking into account possible future savings from regenerative braking); an average systemwide fuel consumption rate for AC Transit buses; and an average "standard" automobile fuel consumption of 16 miles per gallon.

Estimates have been made about the relative diversion of travel to BART from automobile and bus. Inevitably, these are subject to uncertainty. So too are the estimates of the number of "new" trips brought about by the start of BART service.

Obviously, assumptions and estimates different from those made in this analysis will give rise to different results regarding the total fuel consumed in travel by automobile, bus, and BART. No sensitivity analyses have been attempted in this brief discussion. However, it is felt that changes in the assumptions within reasonable ranges would not alter the basic conclusions:

- In terms of energy consumed per seat-mile provided, BART is less fuel-efficient than bus but much more efficient than automobile. Thus, if travel can be diverted from automobile, BART has the potential for considerable energy savings.

- In fact, in a major travel corridor of the Bay Area where much of BART's ridership comes from buses, where automobile occupancy is high, and where BART's load factors in the peak period/reverse direction and off-peak are low, the actual energy savings due to BART are much smaller than the potential. And if the many new trips apparently induced by BART are taken into account, the net energy savings may be negligible.

REFERENCES

DeLeuw, Cather & Company. Case Studies of Transit Energy and Air Pollution Impacts. Report No. EPA-600/5-76-003 prepared for the Office of Energy, Minerals, and Industry, Environment Protection Agency, Washington, D.C., May 1976.

Fels, Margaret Fulton. "Comparative Energy Costs of Urban Transportation Systems," Transportation Research. Volume 9, Number 5. October 1975, pp. 297-308.

Healy, Timothy J. Energy Requirements of the Bay Area Rapid Transit System. Report prepared for the State of California Department of Transportation, November 1973.

Healy, Timothy J. Energy Use of Public Transit Systems. Report prepared for the State of California Department of Transportation, August 1974.

Healy, Timothy J., and Daniel T. Dick. "Total Energy Requirements of the Bay Area Rapid Transit System." University of Santa Clara, California, July 1974.

Hirst, Eric. "Transportation Energy Conservation Policies," Science. Volume 192, Number 4234, April 1976, pp. 15-20.

Lave, Charles A. "The Negative Energy Impact of Modern Rail Transit Systems." Paper prepared for presentation at the Fifty-Sixth Annual Meeting of the Transportation Research Board, January 1977.

Peat, Marwick, Mitchell & Co. Transportation and Travel Impacts of BART: Interim Service Findings. BART Impact Program Document No. FR 6-3-75. Report to Metropolitan Transportation Commission, Berkeley, California, April 1976.

Stuntz, Mayo S. Jr., and Eric Hirst. "Energy Conservation of Urban Mass Transit." Paper presented at the Fifty-Fifth Annual Meeting of the Transportation Research Board, January 1976.

APPENDIX

ANALYSIS OF BART'S ENERGY CONSUMPTION FOR INTERIM SYSTEM OPERATIONS
(June, 1975)

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SUMMARY

BART's energy consumption has undergone the following changes since the inception of service in September 1972:

- Total consumption has risen from 5.8×10^6 kilowatt hours (kwh) per month to a peak of over 17×10^6 kwh per month.

- Energy consumption per production unit has decreased from a peak of 1.7 kwh per passenger mile (kwh/pm) to a low of 0.39 kwh/pm.

- Traction energy has increased from 25% to 70% of total system energy.

A forecast of BART's energy consumption for full system service (e.g., 34 stations, 600 cars, 4.3 million car-miles per month, and 80 million passenger-miles per month) suggests the following energy consumption characteristics for full-system operation:

- A total monthly energy consumption of 27.5 million kwh.

- An energy consumption per production unit of 0.34 kwh/pm.

- Traction energy will be 80% of all energy consumed, while station and maintenance energies will be 17% and 3%, respectively.

BART's energy consumption is comparable to that of other heavy rail transit systems and projections indicate that when full operating levels are achieved, BART will be more efficient than the average within the United States for these systems. This is due mainly to BART's lighter vehicles.

BART vehicles consume less energy, on a per seat-mile basis, than all other modes except buses. Compared with BART's projected traction energy consumption, buses consume between 65% and 85% as much energy per seat-mile. However, it must be realized that BART vehicles travel significantly faster than buses. In addition, BART cars can realize a load factor of about 300% during peak conditions, while buses can only accept 150% to 175% of their seating capacity. Thus, at peak loads, the energy consumed per passenger-mile is essentially equal for the two modes.

ENERGY CONSUMPTION ANALYSIS

Introduction

This Working Paper:

- Describes BART's historical operating energy consumption including:
  - Maintenance energy
  - Station energy
  - Traction energy
- Provides parametric estimates of BART's operating energy consumption based on:
  - Car-miles
  - Passenger-miles
  - Number of cars in the system
- Estimates BART's energy consumption for full-system operations
- Compares BART's energy consumption to that of other rail rapid transit systems and alternative modes

BART's Historical Operating Energy Consumption

BART's energy consumption, as illustrated in Figure 1, is segregated into three main categories:

1. Maintenance energy, which includes all energy consumed in the Concord, Richmond, Oakland, and Alameda shops and yards (except traction energy from the third rail).

2. Station energy, which includes all energy consumed by BART stations and parking lots (e.g., lighting), for the ventilation of the Transbay Tube and Berkeley Hills Tunnel, and for the operation of the BART administration building at the Lake Merritt Station.

3. Traction energy, which is used to propel the cars and to power their auxiliary functions (air conditioners, heaters, lights, etc.), as provided by the 1,000-volt DC third rail.

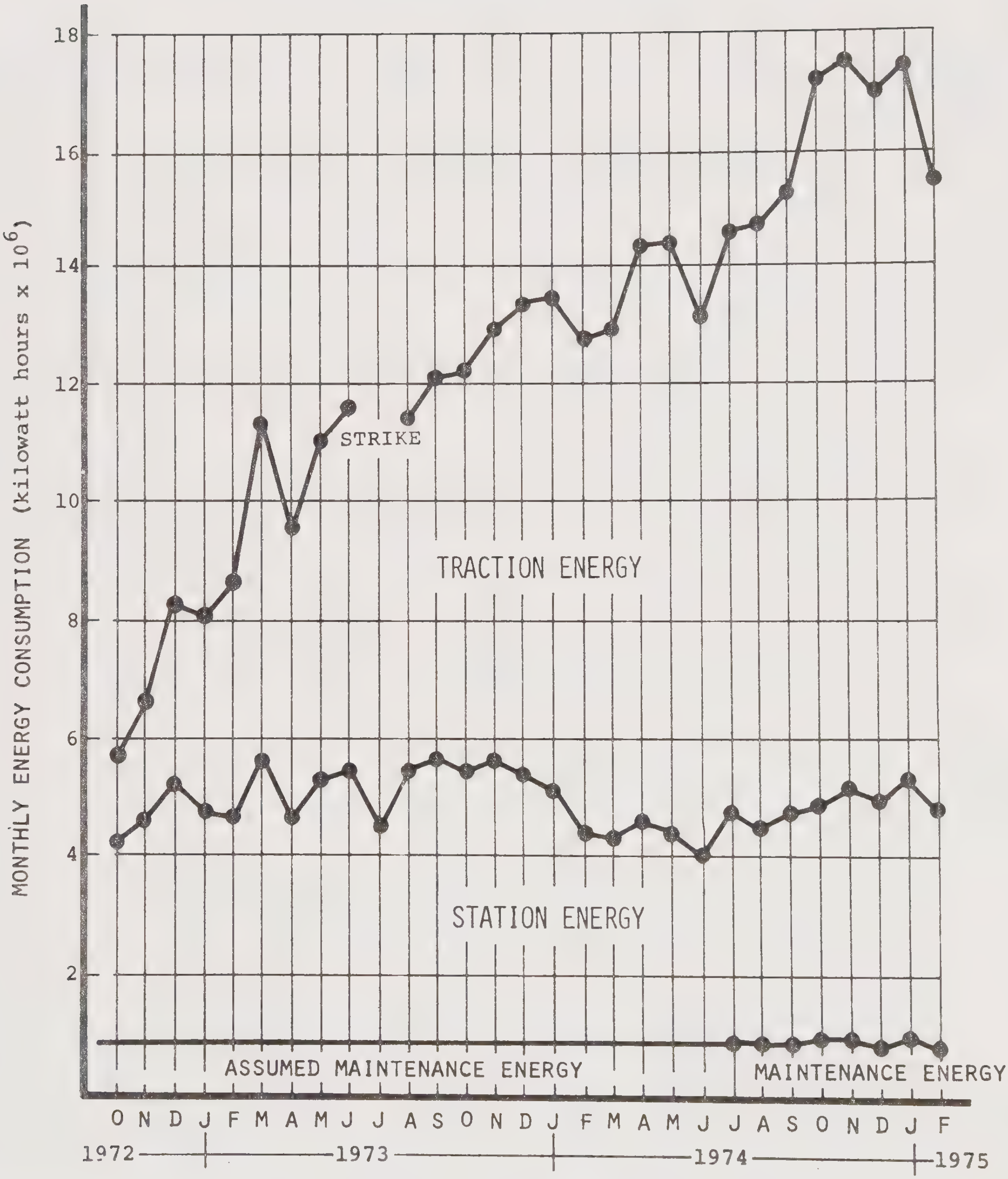

FIGURE 1

HISTORICAL BART MONTHLY ENERGY CONSUMPTION

Maintenance Energy. Only eight months (July 1974 to February 1975) of maintenance energy data are conveniently available from BART files. Acquisition of maintenance energy data for time periods prior to July 1974 would require more time than was available for the present analysis. However, the data that were obtained indicate a very constant rate of energy consumption for maintenance purposes. For the time periods observed, the monthly energy consumption ranged from a high of 0.95×10^6 kilowatt hours (kwh) to a low of 0.82×10^6 kwh with an average of 0.88×10^6 kwh. Considering the relatively small magnitude and the stability of maintenance energy consumption, it is not inappropriate to assume a consumption level of 0.88×10^6 kwh per month prior to July 1974, as indicated in Figure 1.

Station Energy. Subtracting the observed and assumed monthly maintenance energy consumptions from the total of maintenance and station energy consumption (i.e., all nontraction energy consumption) results in the station energy consumption presented in Figures 1 and 2. Prior to August 1973, station energy consumption levels showed wide variations, because of the rapidly increasing levels of BART service and varying degrees of construction activity at stations not yet open. From August through November 1973--when all stations were either in operation, physically complete, or very nearly complete--the monthly energy consumption was approximately 4.6×10^6 kwh. Prompted by the Arab oil embargo, BART implemented energy conservation measures in its station operations beginning December 1973. Despite the fact that the opening of the San Francisco Line introduced eight stations into operation in mid-November 1973, monthly station energy consumption dropped to approximately 3.4×10^6 kwh by February 1974. From this low point, energy consumption began to rise slowly to its present level of about 4.0×10^6 kwh per month; this is probably due to seasonal variations and possibly some slackening of conservation measures.

Traction Energy. Traction energy is consumed by the BART cars for propulsion and for powering their auxiliary functions such as air conditioning, heating, lights, etc. Propulsion energy is used to propel the cars and the payload (i.e., the passengers). Propulsion energy is consumed during operating hours for revenue service and during nonrevenue hours for testing. Auxiliary energy is consumed at all times by most cars, since all cars (except those in the shop for major repairs) are kept "hot" (i.e., the climate control equipment is functioning).

Traction energy consumption has increased steadily since the inception of BART service as the number of car-miles and the number of cars in operation have increased. The reductions in traction energy consumption in June 1974 and February 1975 are associated with corresponding reductions in the number of car-miles of service.

Parameterization of System Energy Consumption

Total system energy consumption is presented in Figure 3 on a per car-mile basis and in Figure 4 on a per passenger-mile basis. These figures suggest the following:

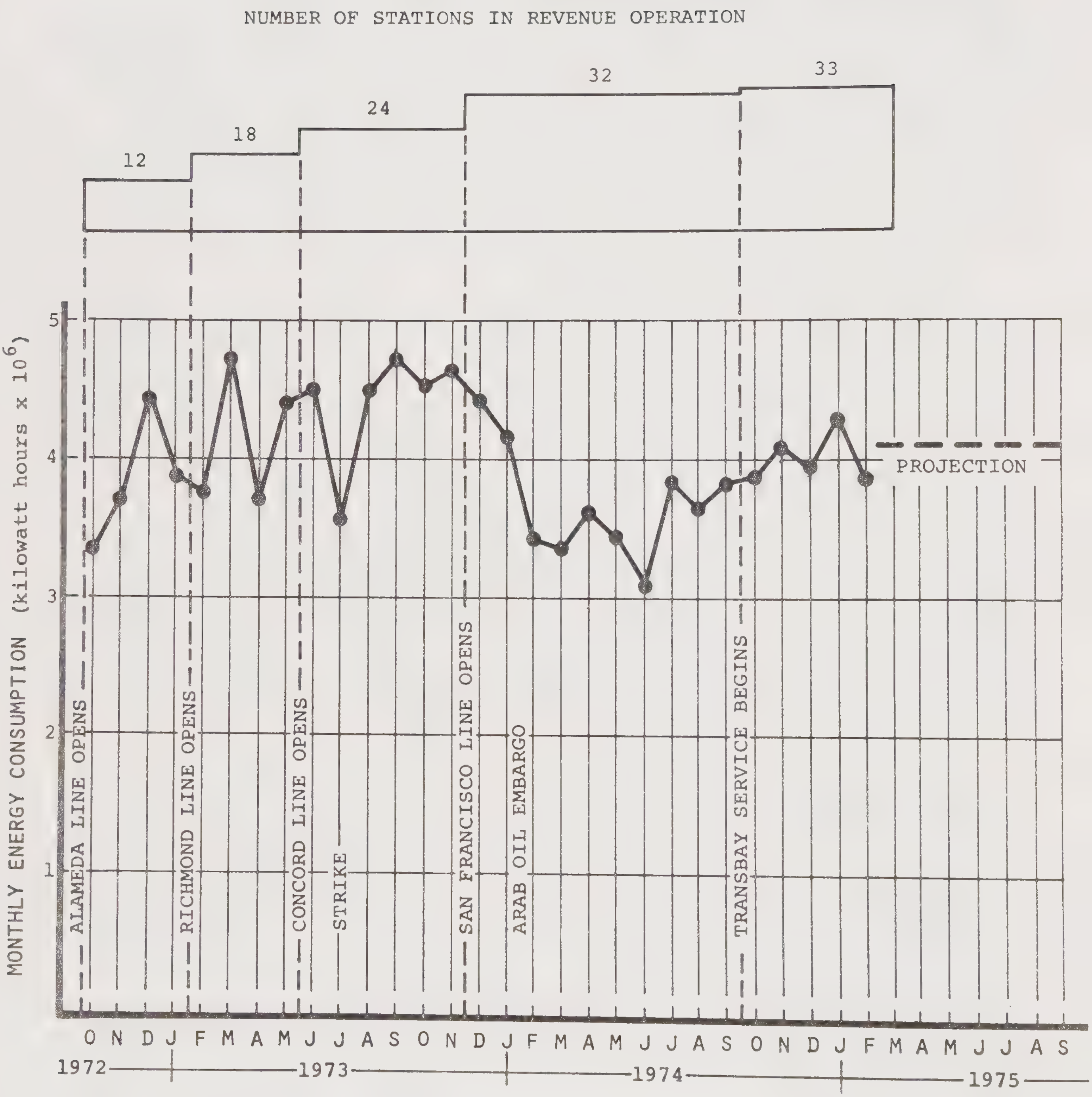

FIGURE 2

HISTORICAL BART MONTHLY STATION ENERGY CONSUMPTION

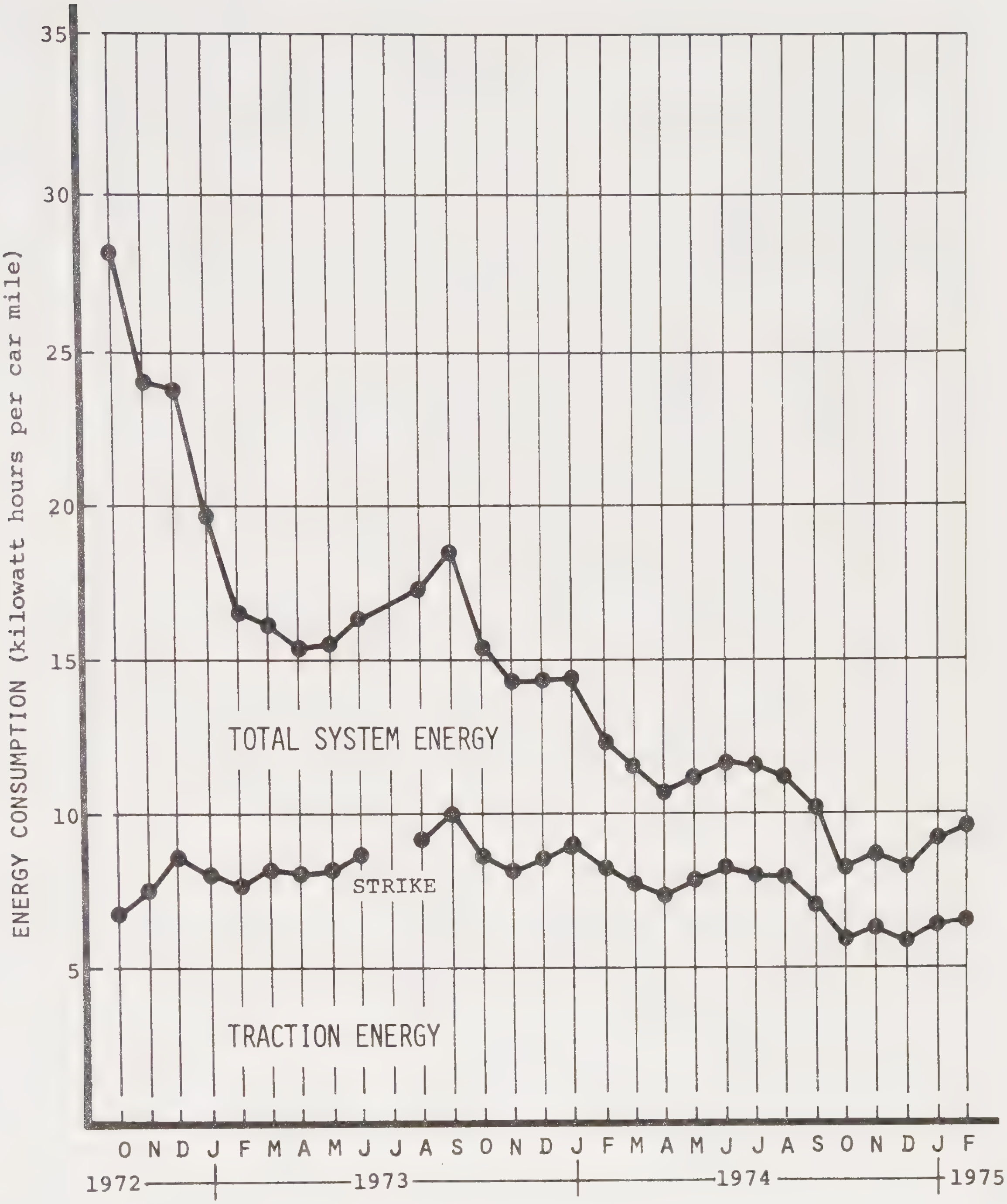

FIGURE 3

BART ENERGY CONSUMPTION PER CAR MILE

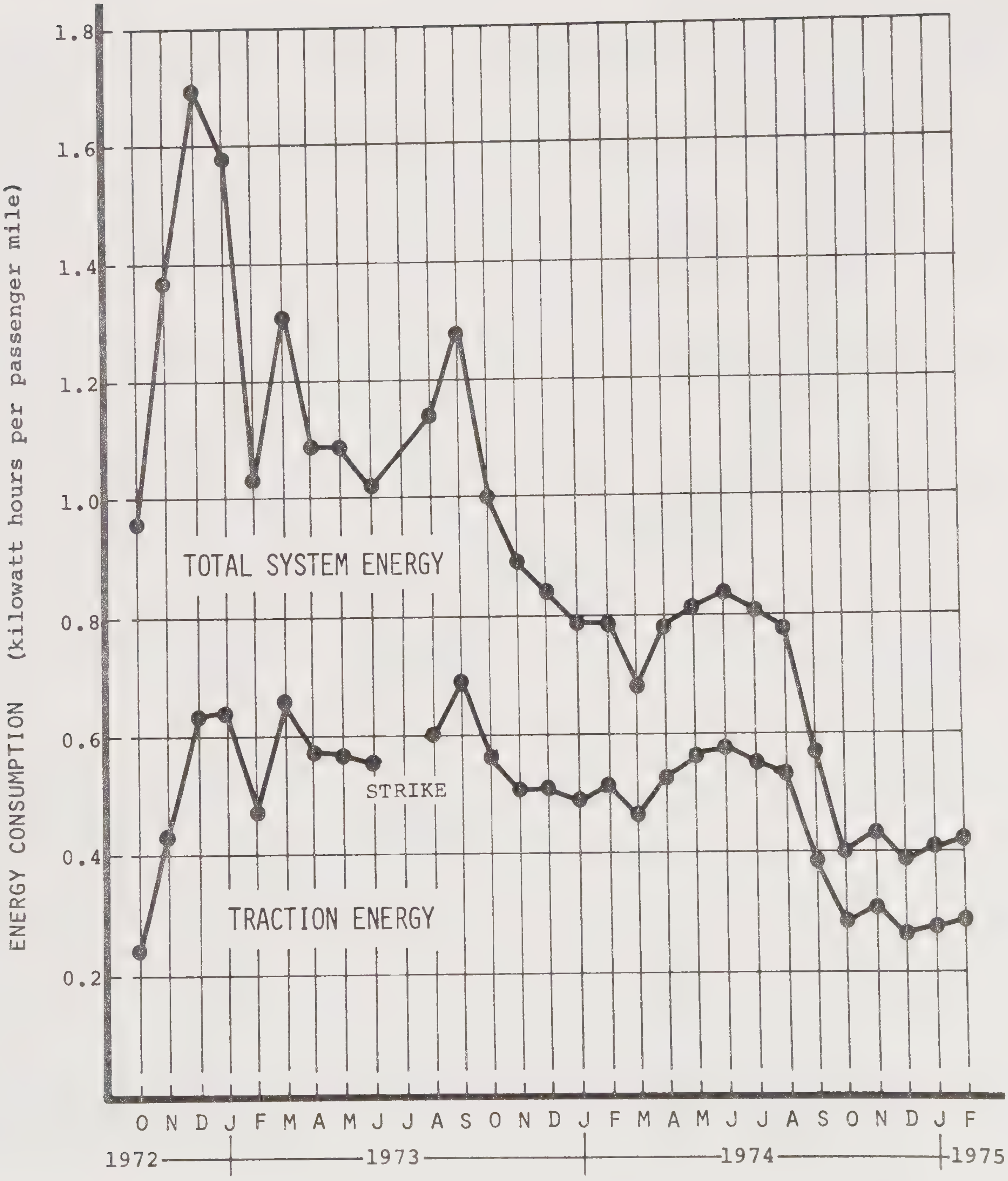

FIGURE 4

BART ENERGY CONSUMPTION PER PASSENGER MILE

- As BART service and patronage have increased, the energy consumption per car-mile and per passenger-mile have decreased to 25% to 30% of original energy consumption. Essentially, the fixed station and maintenance energy consumption is being allocated among a greater volume of production units (car-miles or passenger-miles).

- As BART service and patronage have increased, traction energy has assumed a greater percentage of total energy consumption. During early operations, traction energy comprised approximately 25% of the total energy consumption, whereas presently, it comprises 70%.

- In the period following initiation of transbay BART service, traction energy consumption per car-mile decreased. This was due to the fact that although the number of car-miles (on which the propulsion energy component of traction energy is directly contingent) increased 63% between August and October 1974, the number of cars (on which the auxiliary energy component of traction energy is based) only increased 9%. Traction energy consumption, therefore, increased at a rate between the increases of its two components--21% from August to October--and the traction energy consumed per car-mile decreased.

  Also, in the same period, energy consumption per passenger-mile decreased significantly because of the decrease in energy consumption per car-mile and the increased number of passengers per car.

Forecasts of BART's Energy Consumption

Maintenance Energy. Considering the relative stability of historical maintenance energy consumption with increasing system operations, it appears reasonable to assume that maintenance energy consumption will remain relatively constant in the future. With increased fleet size, the level of activity (and thus energy consumption) may increase slightly. For this analysis, an ultimate monthly maintenance energy consumption of 1.0×10^6 kwh will be used. (Note: The working note describing the TSTB Phase I energy analysis suggested a linear regression analysis with monthly maintenance energy consumption as the dependent variable and the number of days in the month and the number of cars in the system as the independent variables. Such an analysis was performed but the results were inconclusive and are therefore not presented.)

Station Energy. A trend curve was fitted by hand to the post-oil embargo energy consumption data points shown in Figure 2. Assuming that the current revenue hours of BART operation continue, and that the present

policies pertaining to station operating procedures during revenue and nonrevenue periods continue (e.g., turning most station lights off during nonrevenue periods), a steady state of station energy consumption for the 34-station system of approximately 4.1×10^6 kwh per month can be estimated; this is an average monthly consumption of 0.12×10^6 kwh per station.

The estimated station energy consumption of 4.1×10^6 kwh per month assumes the present service level of 70 operational hours per week.

Healy (Ref. 5)* determined that hourly station energy consumption in nonrevenue periods was 92% as great as energy consumption during revenue periods for June of 1973. During the Arab oil embargo, station energy conservation measures were taken that decreased total station energy consumption from a peak of approximately 4.6×10^6 kwh per month to the present stable level of 4.1×10^6 kwh per month (Fig. 2) or a decrease of 11%. Assuming that the majority of energy conservation measures were made during nonrevenue periods, implies that station energy consumption during these periods decreases to 82% of the pre-embargo level. Thus, the hourly energy consumption during nonrevenue periods is assumed as 75% as great as the present hourly consumption during revenue periods and will continue so into the future.

Utilizing this ratio of 0.75:1, the following procedure may be used to estimate monthly station energy consumption for the projected ultimate service level of 140 hours per week (20 hours per day, 7 days per week).

$$E_{70} = (70) \times (K) + (98) \times (0.75K) = 4.1 \times 10^6 \text{ kwh}$$

This results in a value for K of 28.57×10^3 kwh which is then utilized in the following equation:

$$E_{140} = (140) \times (K) + (28) \times (0.75K) = 4.6 \times 10^6 \text{ kwh}$$

where

E_{70} = monthly station energy consumption at the present service level of 70 hours per week

E_{140} = monthly station energy consumption at the ultimate service level of 140 hours per week

K = A constant relating revenue-hour station energy consumption to monthly station energy consumption

*Reference numbers in this working paper correspond to the numbers of publications cited in the Bibliography at the end.

Therefore, the estimated monthly station energy consumption for the ultimate service level of 140 hours per week is approximately 4.6×10^6 kwh or $.14 \times 10^6$ kwh per station. (Note: The working note describing the TSTB Phase I energy analysis suggested a linear regression of the monthly station energy consumption versus the number of days in the month. Such an analysis was performed utilizing both the calendar days in each month and the operating days; however, the results were inconclusive and are therefore not presented.)

Combining station and maintenance energy estimates results in a projected energy consumption of 5.6×10^6 kwh per month. This compares to a monthly station and maintenance energy consumption of 7.1×10^6 kwh projected by Healy (Ref. 5) based on June 1973 observations. The difference between these estimates can largely be attributed to the fact that Healy based his estimate on empirical data obtained prior to the energy conservation measures initiated in the winter of 1973-74.

Traction Energy. A full analysis of traction energy consumption requires that revenue and nonrevenue periods be analyzed separately. Table 1 illustrates the five major elements of traction energy consumption and the key variables affecting these elements. Unfortunately, no record of test car-miles is kept, and there is no convenient way to measure hot car hours, either during revenue or nonrevenue periods. If test car propulsion energy consumption is assumed neglibible relative to other traction energy consumption and the total number of hot car hours is proportional to the number of cars in the system, then the total traction energy consumption can be considered a function of three independent variables: (1) car-miles, (2) passenger-miles, and (3) number of cars in the system.

Utilizing monthly data from the inception of BART service to the present (see Figure 5), several multiple linear regression analyses were performed defining traction energy as the dependent variable and various combinations of car-miles, passenger-miles, and cars in the system as the independent variables. The model incorporating monthly traction energy as the dependent variable and car-miles and cars in the system as the independent variables was the most viable for predictive purposes. Passenger-miles can be omitted as an independent variable due to the very high correlation between passenger-miles and car-miles, as exhibited in Figure 5. The estimated model of traction energy consumption is as follows:

$$E_t = 1740 + \underset{(3.15)}{17.8\,(C)} + \underset{(.00058)}{.0022\,(D_c)}$$

where:

E_t = monthly traction energy consumed (10^3 kwh)

C = number of cars in the system

D_c = car-miles per month

Table 1

TRACTION ENERGY

Dependent Variable	Independent Variable
P_{v1} = Revenue Vehicle Propulsion	D_{v1} = Revenue Car-Miles
P_p = Revenue Payload Propulsion	D_p = Revenue Passenger-Miles
A_1 = Revenue Auxiliary Energy	T_1 = Revenue Hot Car Hours
P_{v2} = Nonrevenue Vehicle Propulsion	D_{v2} = Test Car-Miles
A_2 = Nonrevenue Auxiliary Energy	T_2 = Nonrevenue Hot Car Hours

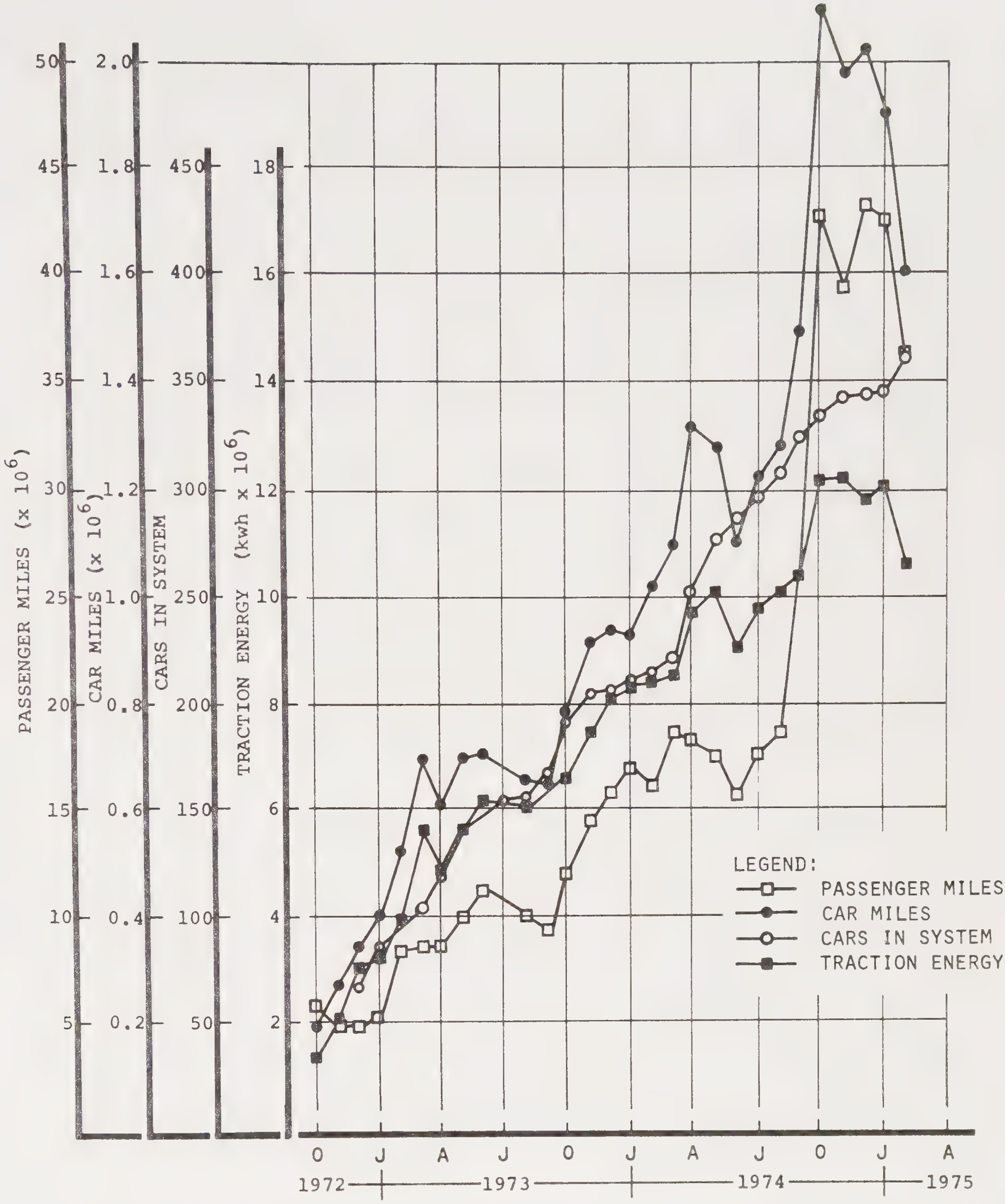

FIGURE 5

HISTORICAL BART MONTHLY TRACTION ENERGY CONSUMPTION

This estimation is of high quality; all of the coefficients have the "correct" sign, the model is significant beyond the 0.001 level of confidence using an F test for the significance of the regression as a whole, and the multiple correlation coefficient (r^2) is 0.98.

Utilizing this equation and assuming a full-system operation of 600 cars and 4,300,000 car-miles per month produces an ultimate system traction energy consumption of 21.9×10^6 kwh per month. This is equivalent to 5.1 kwh per car-mile (kwh/cm) which correlates strongly with Healy's (Refs. 4 and 5) projection of 5.0 kwh/cm.

All BART vehicles are equipped with regenerative braking equipment designed to return power to the system during braking. During the 2-1/2-year period of BART operation for which traction energy consumption data is presented in Figure 5, the regenerative braking system was largely ineffectual in reducing BART's energy consumption because of the relatively large spacing between trains. Further, since February 1975, the power supply system has been separated into distinct "blocks" thereby prohibiting the flow of power from a decelerating to an accelerating train. As train spacings are reduced and if the blocking of the power system is eliminated, the regenerative braking system will act as a power source and reduce the net external power requirements. Under these circumstances, Healy (Ref. 5) has estimated that regenerative braking could supply as much as 0.8 kwh/cm during peak operating periods (i.e., minimum headways) and BART has estimated that the average reduction in traction energy consumption for all operating periods (i.e., peak and off-peak) would be 0.25 kwh/cm. This would result in a 5% reduction in traction energy and a 4% reduction in total system energy consumption.

Forecast of Energy Consumption for Full-System Operation. BART's monthly energy consumption in the period following transbay BART service (October 1974 to February 1975) is compared in Table 2 to corresponding estimates for full BART service. For the purposes of this analysis, full service has been assumed as 4,300,000 car-miles per month and 80,000,000 passenger-miles per month, or about twice the current levels. The projections for each of the three principal components of energy consumption are based on the assumptions and procedures described above.

This simple analysis suggests two major points. First, while total monthly energy consumption will increase about 64% from current operations to the assumed full-system operations, the corresponding energy consumption per car-mile will decrease by about 25%, and the corresponding energy consumption per passenger-mile will decrease by about 19%. Second, the proportion of total energy consumption devoted to traction energy will increase from about 70% under current operations to about 80% under the assumed full-system operation.

Table 2

FORECAST OF BART ENERGY CONSUMPTION
FOR FULL-SYSTEM OPERATIONS

	BART Energy Consumption		
Post Transbay BART (October 1974-February 1975)[a]	Total Per Month (kwh x 10^6)	Per Car-Mile (kwh)	Per Passenger-Mile (kwh)
Traction Energy	11.9	6.0	0.30
Station Energy	4.0	2.0	0.10
Maintenance Energy	0.9	0.5	0.02
Total	16.8	8.5	0.42
Projected Ultimate System[b]			
Traction Energy[c]	21.9	5.1	0.27
Station Energy	4.6	1.1	0.06
Maintenance Energy	1.0	0.2	0.01
Total[d]	27.5	6.4	0.34

a. Based on 350 cars, 2,000,000 car-miles per month, and 40,000,000 passenger-miles per month.

b. Assumes 600 cars, 4,300,000 car-miles per month, and 80,000,000 passenger-miles per month.

c. This does not include consideration of the potential contribution of the regenerative braking system which BART has estimated could reduce traction energy consumption by an average of 5%.

d. This forecast may be contrasted with BART's forecast of total monthly energy consumption of 29.4 x 10^6 kwh for projected ultimate system operation including regenerative braking.

Comparison of BART's Energy Consumption To That of Other Rail Rapid Transit Systems and Other Modes

Table 3 presents the energy consumptions, capacities, and energy consumptions per production unit for modes currently available in the Bay Area. The data for all of the modes except BART have been derived from various secondary sources.

Comparison of BART to Other Rail Rapid Transit Services. A comparison of BART's energy consumption to that of other rail rapid transit services might be based on the energy consumed per seat-mile. However, while BART is designed to seat the majority of passengers, other systems such as the subway systems in New York City, Chicago, and Philadelphia have been designed to provide more limited seating but greater room for standing in order to serve a larger number of people per car. Comparison of the systems on the basis of energy per seat-mile would, therefore, present an erroneous view of the actual situation. Ideally, a production unit more clearly reflecting a vehicle's passenger carrying capabilities irrespective of seating configuration should be utilized. Such a unit which could be utilized in the future is energy consumed per unit floor area per vehicle mile. However, for this analysis, energy consumed per car-mile is used.

It is emphasized that energy consumption data for other systems are available for traction energy only, and do not include maintenance or station energy. Hence, this comparison focuses on BART's traction energy consumption. Presently, BART's traction energy consumption is approximately 10% above the national average probably because of BART's short operating hours, the relatively high percentage of cars which are out of revenue service, and the fact that auxiliary power is consumed by BART vehicles 100% of the time, while revenue service is only available 42% of the time. As BART's operations expand from 24 million to 50 million annual car-miles and from 70 to 140 weekly operating hours, its traction energy consumption (on a per car-mile basis) will decline to 5.1 kwh/cm or 10% below the national average. The main reasons for BART's projected traction power consumption being lower than the national average is that BART cars weigh about 28,000 pounds or 33% less than New York City subway cars. The improvement in BART's traction energy efficiency relative to the other rail rapid transit systems because of the lighter weight of its cars is partially offset, however, by increased drag due to the high operating speeds (80 mph) of BART cars, in addition to high rates of acceleration.

Comparison of BART to Other Modes. Inasmuch as the units for describing the energy consumption of electrically powered vehicles are different from those used to describe the energy consumption of vehicles powered by internal combustion engines, both estimates were converted to the common units of British thermal units (Btu) per production unit (e.g., seat-miles or passenger-miles). This conversion assumed an efficiency factor of 30% for the generation and transmission of electrical power. It should be recognized, however, that other sources besides petroleum can be utilized to generate electricity.

Table 3

MODAL ENERGY CONSUMPTION

Mode	Energy Consumption	Weight (lbs)	Seats	Weight per Seat (lbs)	Btu/sm[a]	Btu/pm[b] Load Factor 25%	50%	100%
Auto (average urban)[c]	11.5 mpg	4,000	6	670	1,810	7,240	3,620	1,810
Auto (subcompact)[c]	25 mpg	2,000	4	500	1,250	5,000	2,500	1,250
Jitney[c]	8 mpg	8,000	8	1,000	1,950	7,800	3,900	1,950
Demand Responsive Bus[c]	4.2 mpg	n.a.	19		1,570	6,280	3,140	1,570
Fixed Route Bus[c]	3.6 mpg	20,000	50	400	690	2,760	1,380	690
Express Bus[c]	4.8 mpg	20,000	50	400	520	2,080	1,040	520
Commuter Rail[c,d]	1,030 Btu/sm	Locomotive: 300,000 Cars: 180,000	500	1,800[e]	1,030	4,120	2,060	1,030
Trolley Coach[f]	3.62 kwh/cm		50		830	3,320	1,660	830
Street Car (LTV)[f]	4.49 kwh/cm		55		930	3,720	1,860	930
Heavy Rail Transit[f,g,h] (National Average)	5.50 kwh/cm	85,000			n.a.	n.a.	n.a.	n.a.
BART[i]								
Present System		57,000	72	790				
Traction	6.0 kwh/cm				950	3,390[j]	1,900	950
Station and Maintenance	2.5 kwh/cm				400	1,430	800	400
Total	8.5 kwh/cm				1,350	4,820	2,700	1,350
Ultimate System								
Traction[k]	5.1 kwh/cm				810	3,240	1,620	810
Station and Maintenance	1.3 kwh/cm				200	800	400	200
Total	6.4 kwh/cm				1,010	4,040	2,020	1,010

n.a. = not available.

See continuing page for footnotes.

Table 3 (cont.)

NOTES

a. British thermal units per seat-mile. Assume 125,000 Btu per gallon of gasoline. This is as reported in References 4, 8, 9, and 10. For electrical energy, the direct conversion is 3,412 Btu/kwh.

b. British thermal units per passenger-mile.

c. Energy consumption, vehicle weight, and seating capacity reported in Reference 4.

d. Reference 4 reported the energy consumed by the Southern Pacific commuter service operating between San Francisco and San Jose. These trains consist mostly of double-deck cars with 150-seat capacities; however, there are several single-level cars with approximately half the capacity. The energy consumption and capacity as reported in this table are for an "average" train. The specific energy (Btu/sm) decreases significantly for peak hour trains that have up to 1,300 seats and increases for off-peak trains that may have only one car.

e. Weight calculated as follows:

   Car weight = (180,000 lbs/car) ÷ (150 seats/car) = 1,200 lbs/seat
   Locomotive weight = 300,000 lbs ÷ 500 seats = 600 lbs/seat
   Train weight = 1,200 lbs/seat + 600 lbs/seat = 1,800 lbs/seat

f. Energy consumption from Reference 12. Seating capacity is assumed.

g. Since New York City represents the majority of heavy rail rapid transit usage in the United States (Table 6B.5, Ref. 6), the weight of a New York City transit car (Ref. 1) will be used for this category.

h. Energy consumed per seat-mile is not applicable for this mode as many rail transit cars, New York City's rail rapid transit in particular, are designed for standees as much as they are for seated passengers.

i. Energy consumption from BART records and PMM&Co. forecasts as presented in this working note.

j. These specific energy consumptions for the present system reflect the 28% load factor that was experienced by BART in February 1975.

k. This does not include the benefits of regenerative braking, which may decrease net traction energy requirements by as much as 0.8 kwh/cm (Ref. 5).

The following discussion focuses on the comparative energy consumption per seat-mile of the various modes. To the extent that the load factors of the various modes are significantly different, or could be differentially modified by private or public sector actions, it would also be desirable to assess the comparative energy consumption per passenger-mile. Presently, BART experiences a total system consumption of 1,350 Btu per seat-mile (Btu/sm) which includes 950 Btu/sm for traction energy and 400 Btu/sm for station and maintenance energy. Projections indicate that BART's energy consumption for full-system operations will decrease 25% from the present specific consumption to 1,010 Btu/sm; this includes 810 Btu/sm for traction energy.

As only traction energy consumption is readily available for all modes except BART, the comparison of BART and the other modes will be based solely on traction energy consumption. For the modes represented in Table 3, the energy consumed ranges from 520 Btu/sm for an express bus to 1,950 Btu/sm for an eight-passenger jitney; thus, the most energy efficient modes are the express and fixed route buses. This is contrary to the commonly held belief that a steel wheel on steel rail technology has the greatest energy efficiency. It must be realized, however, that traction energy consumption is a function of vehicle weight, acceleration, operating speed, and auxiliary energy consumption. While BART is a steel wheel on steel rail technology, several items must be noted when comparing it to the bus: (1) BART has almost twice the weight to seat ratio; (2) it employs a much higher rate of acceleration; (3) it travels up to 80 mph as opposed to 55 mph for an express bus and 30 to 35 mph for a regular fixed route bus; and (4) it has a climate control system that operates 24 hours a day. These elements cause BART to consume greater amounts of traction energy per seat-mile than bus despite the intrinsic energy effectiveness of its technology.

Bibliography

1. Casey, Robert F. Summary Data for Selected New Urban Transportation Systems. Prepared for the U.S. Department of Transportation, Office of the Secretary, Office of Systems Analysis and Information, November 1972.

2. DeLeuw Cather & Co. Characteristics of Urban Transportation Systems, a Handbook for Transportation Planners. Prepared for the U.S. Department of Transportation, Urban Mass Transit Administration, May 1974.

3. Goss, W. P. and J. G. McGowan. Energy Requirements for Passenger Ground Transportation Systems. ASME paper 73-ICT-24, 1973.

4. Healy, T. J. Energy Use of Public Transit Systems. Prepared for the State of California Department of Transportation, Santa Clara, California, August 1, 1974.

5. Healy, T. J. Energy Requirement of the Bay Area Rapid Transit System. Prepared for the State of California Department of Transportation, Santa Clara, California, November 1973.

6. Institute For Defense Analysis. Economic Characteristics of the Urban Public Transportation Industry, Washington, 1972.

7. Lansing, Neal F. Transportation Energy in Southern California. Prepared for Southern California Association of Governments, 1974.

8. Lansing, Neal F. and Howard R. Ross. Energy Consumption by Transit Mode. Prepared for Southern California Association of Governments, March 10, 1974.

9. Masey, Alfred C. and Robert L. Paullin. Transportation Vehicle Energy Intensities (A Joint DOT/NASA Reference Paper), National Aeronautics and Space Administration, Washington, D.C., June 20, 1974.

10. Rice, Richard A. System Energy as a Factor in Considering Future Transportation, Paper No. 70-WA/Ener-8, American Society of Mechanical Engineers, 1970.

11. State of California Department of Transportation. Energy Intensiveness of Transportation Systems, September 26, 1974.

12. American Public Transit Association. Transit Fact Book, 1974-1975 Edition, Washington, D.C., March 1975.

13. Alan M. Voorhees & Associates, Inc. Energy Efficiencies of Urban Passenger Transportation. Technical Study Memorandum No. 9. Prepared for Highway Users Federation, May 1974.

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